PHOTOMETRIC OBSERVATIONS OF THE SUPERNOVA 2009nr

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Abstract – We present the results of our *UBVRI* CCD photometry for the second brightest supernova of 2009, SN 2009nr, discovered during a sky survey with the telescopes of the MASTER robotic network. Its light and color curves and bolometric light curves have been constructed. The light-curve parameters and the maximum luminosity have been determined. SN 2009nr is shown to be similar in light-curve shape and maximum luminosity to SN 1991T, which is the prototype of the class of supernovae Ia with an enhanced luminosity. SN 2009nr exploded far from the center of the spiral galaxy UGC 8255 and most likely belongs to its old halo population. We hypothesize that this explosion is a consequence of the merger of white dwarfs.

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INTRODUCTION

SN 2009nr was discovered in the CCD images obtained with the telescope of the MASTER robotic network (Lipunov et al. 2010) in Blagoveshchensk on December 22, 2009; the report on the discovery was published on January 6, 2010 (Balanutsa and Lipunov 2010). The SN brightness at the time of its discovery was about $13^m.6$, which made it the second brightest SN discovered in 2009 (after SN 2009ig). On January 6, 2010, SN 2009nr was independently discovered during observations as part of the supernova search program at

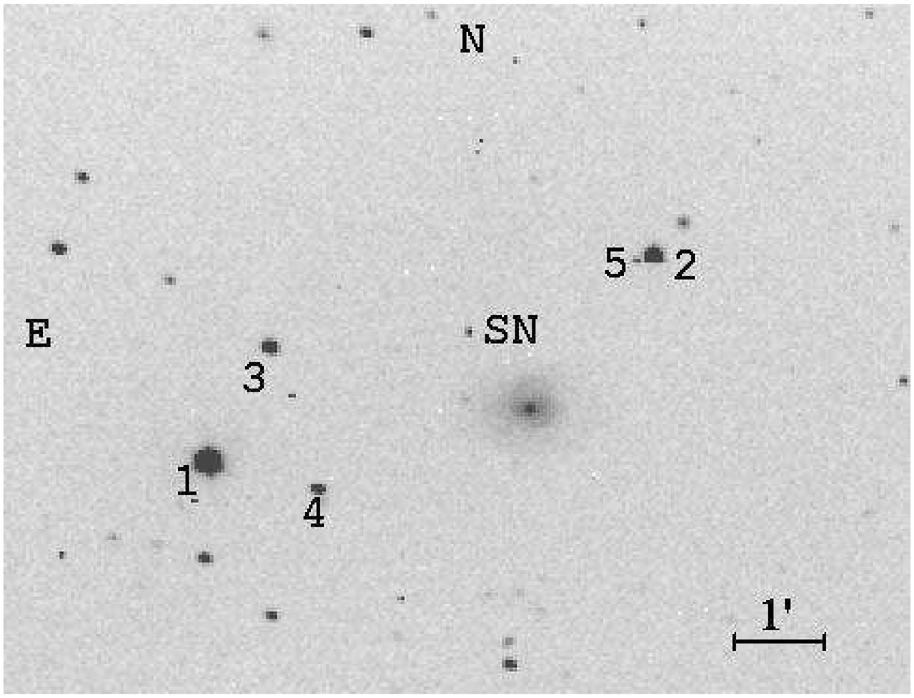

Figure 1: SN 2009nr and the comparison stars. The image was obtained at S50 with the R filter

the Lick Observatory (Li et al. 2010). According to Balanutsa and Lipunov (2010), the coordinates of SN 2009nr are $\alpha = 13^{\rm h}10^{\rm m}58^{\rm s}.95; \delta = +11°29'29''.3$ (J2000.0); Li et al. (2010) give the last digits $58^{\rm s}.94$ and $29''.6$. The SN was $36''$ east and $50''$ north of the center of the Scd galaxy UGC 8255. Foley and Esquerdo (2010) reported that the spectrum of SN 2009nr was taken on January 7, 2010, with the 1.5-m Whipple Observatory telescope; it showed that the object belongs to the class of SNe Ia similar to SN 1991T. SN 2009nr was found in the ASAS images, which made it possible to trace its light curve near the maximum (Khan et al. 2011).

OBSERVATIONS AND REDUCTIONS

We performed our photometric CCD observations of SN 2009nr with the following instruments (their abbreviated designations are given in parentheses): the telescopes of the MASTER robotic network in Kislovodsk with V, R filters (MK) and in Blagoveshchensk without filters (MB) (Lipunov et

Table 1: Magnitudes of local standard stars

Star	U	σ_U	B	σ_B	V	σ_V	R	σ_R	I	σ_I
1	13.42	0.03	12.80	0.02	11.88	0.01	11.38	0.01	10.91	0.01
2	14.68	0.04	14.36	0.03	13.58	0.02	13.15	0.01	12.73	0.02
3	15.75	0.05	15.58	0.02	14.89	0.02	14.49	0.02	14.12	0.02
4	16.67	0.05	16.49	0.03	15.74	0.03	15.32	0.03	14.94	0.03
5	20.45	0.08	19.28	0.05	17.78	0.05	16.87	0.05	16.00	0.05

al. 2010); the 1-m and 60-cm telescopes of the Simeiz Observatory (Crimean Astrophysical Observatory) with a VersArray 512FUV camera and B, V, R filters (C100, C60); the 50-cm telescope of the Astronomical Institute of the Slovak Academy of Sciences in Tatranska Lomnica with an ST-10XME CCD camera and U, B, V, R, I filters (S50); the 20-cm meniscus telescope of the Sternberg Institute in Moscow with an AP-7p camera in the B, V, R, I bands (M20); and the 2-m Faulkes Telescope North (FTN) with u, B, V, R, i filters.

We measured the SN brightness relative to the comparison stars by the method of PSF photometry in the IRAF[1] DAOPHOT package. The galaxy's background near the SN is negligible and does not affect the accuracy of our photometry. The comparison stars are shown in Fig. 1; their magnitudes are given in Table 1. The brighter stars 1 and 2 were calibrated using standards from Landolt (1992) and standard stars in the cluster M67 (Chevalier and Ilovaisky 1991) on the images obtained in March 2010 with M20 and in March 2011 with the 70-cm Sternberg Astronomical Institute reflector. For the remaining stars, we used SDSS[2] photometric data reduced to the $UBVRI$ system by means of relations from Chonis and Gaskell (2008). These magnitudes are in good agreement with the calibration results for stars 3 and 4 from our observations, which, however, have a fairly low accuracy.

The equations for the reduction of instrumental magnitudes to standard ones were derived for C100, C60, M20, and S50 from observations of the cluster M67. Since the same CCD camera and set of filters were used for C100 and C60, the reduction coefficients are identical. The coefficients do not differ greatly from those in Tsvetkov et al. (2008) and Elmhamdi et al. (2011): they are rather small for the V and R bands; for the B band, they are $K_B =$

[1]IRAF is distributed by the NOAO, which are operated by the AURA, Inc., under contract with the NSF

[2]http://www.sdss.org

$-0.15, -0.12, 0.15$ for C100, M20, and S50, respectively; for the I band, they are $K_I = -0.5, -0.04$ for M20 and S50. Since we have no data for the FTN and MASTER that would allow the reduction equations to be established, we applied no corrections for the possible deviations of the instrumental system from the standard one. The V and R filters at the MASTER telescopes and the B, V, R filters at the FTN realize the standard Johnson-Cousins system (Bessell 1990); therefore, the coefficients must be small. The u and i filters realizing the SDSS system are used at the FTN, but we, nevertheless, calibrated the images in these filters by the U and I magnitudes. This should not introduce significant errors for the U magnitudes, because the response curve for the SDSS u band is close to the standard U band. However, systematic errors for the I magnitudes are possible; accordingly, we increased the errors in the magnitudes in Table 2.

The MASTER images without a filter in which SN 2009nr was discovered were calibrated by the V magnitudes. The subsequently obtained images without a filter were not reduced, because there were much data obtained with filters in this period.

The results of our SN brightness measurements are presented in Table 2.

RESULTS OF OUR OBSERVATIONS

The light curves are shown in Fig. 2. We present the results from Khan et al. (2011), which are in good agreement with our magnitudes in all filters, along with other data. The light curves of SN 1991T (Lira et al. 1998), which belongs to the same SN Ia subclass as SN 2009nr, are shown for comparison. The points of maximum light in the $V$and I bands for SN 2009nr can be found directly from the observational data: $V_{max} = 13.73 \pm 0.08, I_{max} = 14.07 \pm 0.06, t_{Vmax} = \mathrm{JD}2455194 \pm 1, t_{Imax} = \mathrm{JD}2455192 \pm 1$. The light curves of SN 1991T near the maximum are in good agreement with those of SN 2009nr; the difference begins 20-30 days after the maximum, when the decline rate of SN 2009nr becomes higher in all bands except B. The parameter Δm_{15} (the brightness decrease in 15 days after the maximum) for the V light curve can be directly determined; it is 0.59 ± 0.05. For SN 1991T and for SNe 1998es and 1999aa, which also belong to the SN Ia 1991T subclass (Hicken et al. 2009; Jha et al. 2006; Tsvetkov and Pavlyuk 2004), the values of $\Delta m_{15}(V)$ are close to this value (being, respectively, 0.62, 0.59, and 0.58). For these three SNe, $\Delta m_{15}(B)$ is approximately the same, about 0.8 (Hicken et al. 2009); it can be assumed that its value is close that for SN 2009nr. The decline rates in the phase interval 100-160 days after the

Table 2: Observations of SN 2009nr

JD 2455000+	U	σ_U	B	σ_B	V	σ_V	R	σ_R	I	σ_I	Tel.
188.40					13.99	0.04					MB
188.43					13.99	0.04					MB
196.58					13.80	0.04	13.73	0.03			MK
196.61					13.79	0.03	13.71	0.04			MK
197.47					13.82	0.03	13.74	0.04			MK
197.48					13.80	0.13	13.72	0.03			MK
198.54					13.80	0.03	13.74	0.03			MK
201.51					13.90	0.03	13.85	0.03			MK
203.61					13.96	0.04	13.88	0.12			MK
208.09	14.96	0.07	14.90	0.05	14.25	0.07	14.24	0.05			FTN
213.70	15.62	0.10	15.46	0.03	14.61	0.03	14.49	0.03	14.51	0.03	S50
216.59					14.87	0.05	14.46	0.04			MK
219.07	16.17	0.09	15.94	0.05	14.81	0.05	14.53	0.05	14.58	0.08	FTN
219.69	16.09	0.08	15.92	0.04	14.86	0.03	14.63	0.03	14.56	0.03	S50
234.45			16.56	0.19	15.55	0.15	15.30	0.07	15.01	0.17	M20
236.55					15.83	0.09	15.30	0.08			MK
238.55					15.83	0.10	15.46	0.08			MK
244.47			16.93	0.20	15.99	0.12	15.66	0.11			M20
253.11	17.35	0.07	17.03	0.04	16.20	0.05	15.98	0.05	16.09	0.08	FTN
259.61			17.10	0.06	16.37	0.03	16.26	0.03			C100
266.44			17.20	0.03	16.53	0.02	16.48	0.02			C100
267.42							16.69	0.14			M20
279.57			17.45	0.05	16.89	0.04	16.84	0.04	17.19	0.07	S50
305.40			17.78	0.06	17.54	0.03	17.69	0.03			C60
309.43					17.44	0.17	17.58	0.19			C60
315.43							17.92	0.10			C60
317.41							17.95	0.10			C60
323.97	18.81	0.08	18.14	0.05	17.73	0.07	18.08	0.05	18.36	0.12	FTN
344.38					18.26	0.07	18.62	0.08			C60
345.29			18.26	0.08	18.26	0.06	18.55	0.06			C60
352.31			18.37	0.07	18.44	0.05	18.93	0.11			C60
357.39					18.42	0.07	19.05	0.12			C60
369.36							19.43	0.25			C60

Note: the errors of the published paper are corrected in this version of Table 2

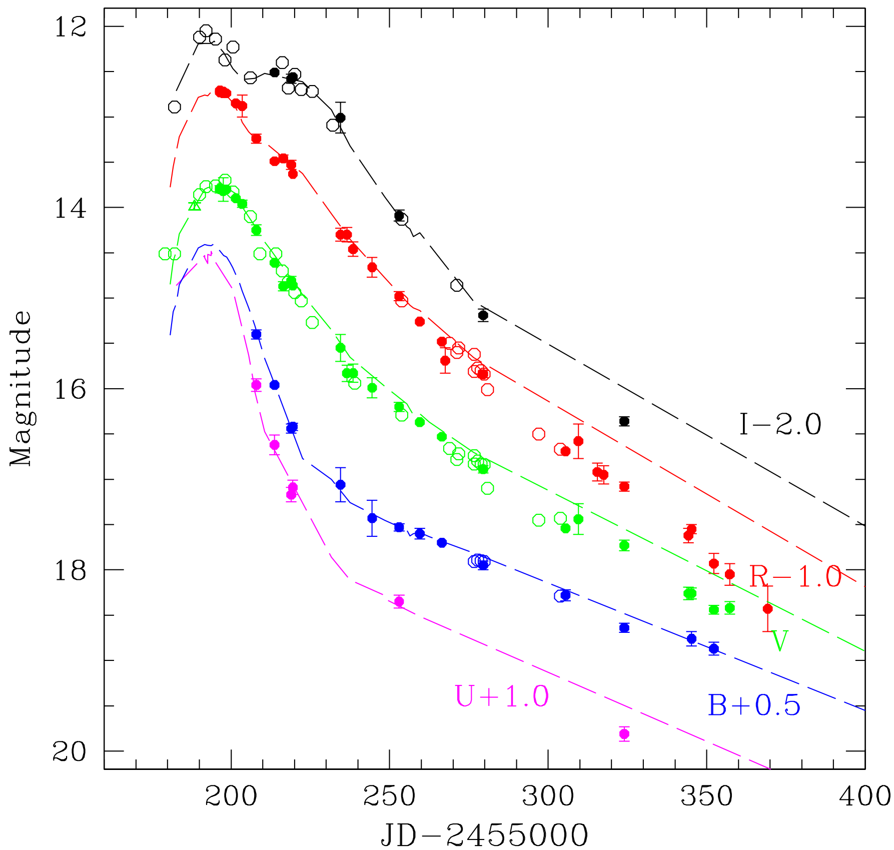

Figure 2: Light curves of SN 2009nr. Our data obtained with and without filters are indicated by the filled circles and triangles, respectively. The open circles represent the data from Khan et al. (2010). The dashed lines are the light curves of SN 1991T

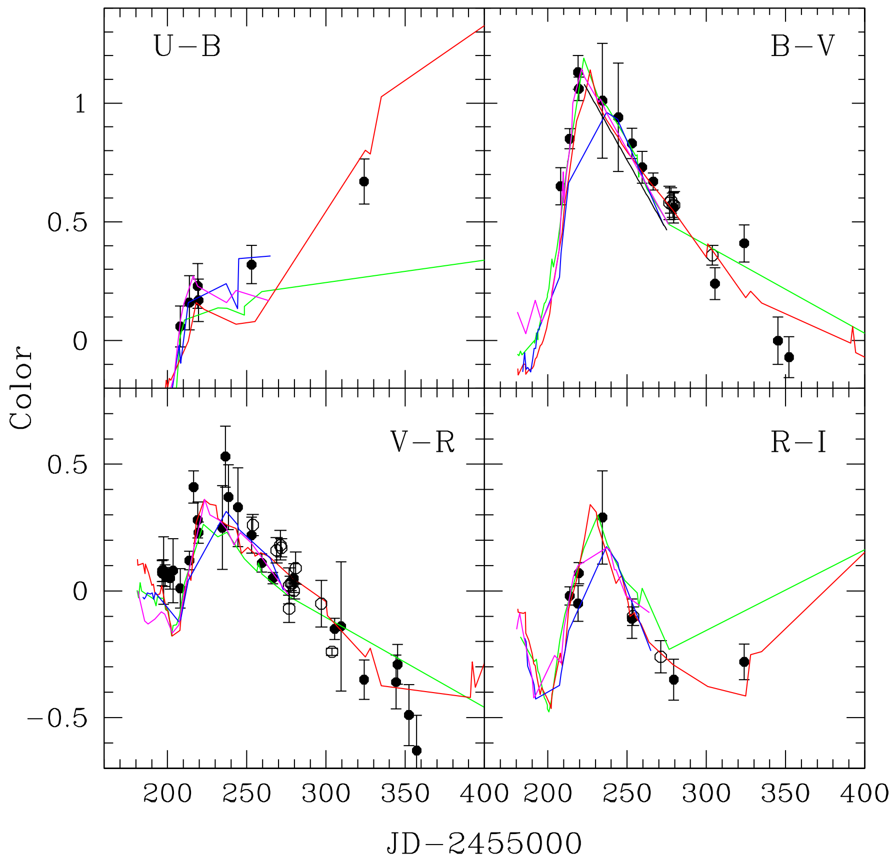

Figure 3: Color curves of SN 2009nr. Our data and the data from Khan et al. (2010) are indicated by the filled and open circles, respectively. The color curves of several supernovae are indicated by the lines: SN 1991T (green), SN 1998es (blue) SN 2003du (red), SN 1999aa (magenta). The black line on the $B-V$ diagram is the Lira-Phillips relation

maximum in the B, V, R bands are, respectively, 1.4, 2.0, 2.6 magnitudes in 100 days. Comparison with SN 1991T and the "normal" SN Ia 2003du (Stanishev et al. 2007) shows that the decline rate in this phase interval in the B band is approximately the same for the three objects, but it differs in the V and R bands, with the lowest and highest values being observed for SN 2003du and SN 2009nr, respectively.

The color curves of SN 2009nr are shown in Fig. 3, where they are compared with those for SNe 1991T, 1998es, 1999aa, and 2003du. The color curves of SN 2009nr, 1999aa, and 2003du were corrected for the extinction in our Galaxy, respectively, $E(B-V)_{Gal} = 0.03, 0.04, 0.01$ (Schlegel et al. 1998), while the color curves of SN 1991T and 1998es were corrected for the total extinction assumed to be the same for them, $E(B-V)_{tot} = 0.15$ (Lira et al. 1998; Tsvetkov and Pavlyuk 2004). Figure 3 also plots the Lira-Phillips relation (Phillips et al. 1999) showing the time dependence of $(B-V)$ in the phase interval 30-90 days for most of the SNe Ia that suffered no extinction. The color curves of SN 2009nr exhibit no noticeable reddening, which confirms the conclusion by Khan et al. (2010) about the absence of extinction in the host galaxy. Note that the $(U-B)$, $(V-R)$, and $(R-I)$ color curves of SN 2009nr differ from those for SN 1991T and show the greatest similarity to the color curves of the normal SN Ia 2003du.

For the distance modulus of the galaxy UGC 8255, we take the value obtained from its radial velocity corrected for the velocity field of the Virgo cluster neighborhood with the Hubble constant $H_0 = 73$ km s^{-1}Mpc^1, μ=33.44[3]. The absolute magnitude of SN 2009nr at maximum light is then $M_V = -19.8$. This is a very high luminosity for SNe Ia, even for the SN 1991T subclass distinguished by an enhanced luminosity. The light curve of SN 2009nr in absolute V magnitudes is shown in Fig. 4, where the light curves of SNe 1991T, 1998es, 1999aa, and 2003du are plotted for comparison. The color excesses adopted for these supernovae are given above; the extinction was calculated at $R_V = 3.1$. The distance moduli taken for SNe 1998es, 1999aa, and 2003du are, respectively, μ=33.19,33.89,32.50; they were calculated in the same way as for UGC 8255 and were obtained from the same source; the distance modulus for SN 1991T, μ=30.76, was determined from observations of Cepheids (Saha et al. 2006). Figure 4 also shows the "quasi-bolometric" light curves of the same SNe obtained by integrating the flux in the range from U to I. The bolometric light curves and the light curves in absolute

[3]http://nedwww.ipac.caltech.edu/

V magnitudes for SNe 2009nr and 1991T nearly coincide up to a phase of 80 days; the difference is observed only at later stages. SN 1998es is slightly brighter than SN 2009nr, while SNe 1999aa and 2003du are considerably fainter.

According to "Arnetts rule" (Arnett 1982), the luminosity of SNe Ia at maximum light is determined by the rate of energy release during radioactive ^{56}Ni decay. The simple equations proposed, for instance, by Stritzinger et al. (2006) and Hayden et al. (2010) relate the mass of ^{56}Ni synthesized during the explosion to the bolometric luminosity (or absolute V magnitude) and the time interval from the explosion to maximum light. Assuming that the maximum light of SN 2009nr in the V band occurred 19.7 days after the explosion (Khan et al. 2011), we find $M(^{56}\mathrm{Ni}) = 0.73M_\odot$ from the formula for the bolometric luminosity and $M(^{56}\mathrm{Ni}) = 1.07M_\odot$ from the formula for the absolute V magnitude. The difference between these estimates is partly explained by the fact that the quasi-bolometric luminosity we derived disregards the ultraviolet and infrared radiation; the ^{56}Ni mass estimated in this way should be increased by 10-20%. We obtain the following ^{56}Ni mass estimates for SNe 1991T, 1998es, 1999aa, and 2003du based on their absolute magnitudes and bolometric luminosities by assuming the mean time of maximum light to be 19 days: 1.00, 0.73; 1.08, 0.89; 0.58, 0.43; 0.48, 0.37. SN 2009nr shows a similarity to SNe 1991T and 1998es, while the ^{56}Ni mass estimates for SNe 1999aa and 2003du are almost a factor of 2 lower. It can be noted that, by its spectroscopic characteristics, SN 1999aa is believed to be an intermediate object between the "normal" SNe Ia and the SN 1991T-type SNe (Garavini et al. 2004).

Several software packages have been developed in recent years to determine the light-curve parameters for SNe Ia (see, e.g., Kessler et al. 2009b; Conley et al. 2008; Burns et al. 2011). We reduced our observations of SN 2009nr using the SNOOPY code (Burns et al. 2011) based on the light-curve standardization technique developed by Prieto et al. (2006). Two versions of the code were applied. The first allows one to determine the maximum light in the B, V, R, I bands, the time of maximum in the B band t_{Bmax}, and the parameter Δm_{15} (it corresponds to $\Delta m_{15}(B)$ but is determined by the light-curve fitting in all filters); the second provides estimates of the extinction in the host galaxy $E(B-V)_{host}$, its distance modulus μ, t_{Bmax}, and Δm_{15}.

The following results were obtained.

The first version: $B_{max} = 13.66 \pm 0.02, V_{max} = 13.66 \pm 0.02, R_{max} = 13.64 \pm 0.02, I_{max} = 14.08 \pm 0.02, t_{Bmax} = \mathrm{JD}2455192.3 \pm 0.3, \Delta m_{15} = 0.96 \pm$

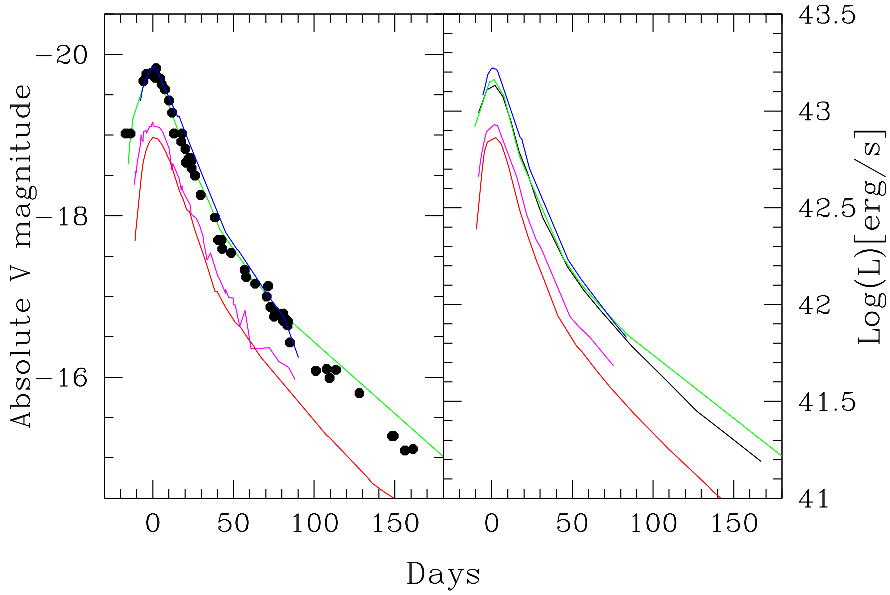

Figure 4: Light curve of SN 2009nr in absolute V magnitudes (left panel, filled circles) and quasi-bolometric light curve (right panel, black line). For comparison, the light curves of SN 1991T, 1998es, 1999aa, and 2003du are shown (by the same lines as those in Fig. 3). The time is given in days since the maximum in the V band

0.02. The second version: $E(B-V)_{host} = 0.11 \pm 0.03, t_{Bmax} = \text{JD}2455192.0 \pm 0.2, \Delta m_{15} = 0.82 \pm 0.03, \mu = 32.93 \pm 0.04$.

The estimates of the maximum light in the V and I bands obtained in this way virtually coincide with those determined directly from observational data; the code also makes it possible to determine B_{max} and R_{max}.The t_{Bmax} estimates obtained by the two versions of the code almost coincide; the maximum in B occurred about two days earlier than the maximum in V, which is typical of SNe Ia. However, the values of Δm_{15} found by the two versions of the SNOOPY code slightly differ, while the estimates of $E(B-V)_{host}$ and μ do not agree very well with those found by analyzing the $(B-V)$ color curves and from the redshift of the galaxy UGC 8255. Some differences in the behavior of the light and color curves of SN 2009nr belonging to the SN 1991T subtype from most of the "normal" SNe Ia are probably responsible for these discrepancies. Note that the absolute magnitude of SN 2009nr calculated with SNOOPY is $M_V = -19.6$, which is rather close to our previous estimate, but SNOOPY adopts an excessively large extinction and, accordingly, a smaller distance.

DISCUSSION

Our study of SN 2009nr reveals its great similarity to SN 1991T in both light-curve shape and luminosity. Noticeable differences include the higher decline rate of SN 2009nr at the late stage, which manifests itself in both U, V, R, I light curves and "quasibolometric" light curves, and the differences in color curves.

The luminosity of SN 2009nr is very high, but it falls nicely on the plot of absolute V magnitude against decline rate presented in Hicken et al. (2009).

SN 2009nr is located far from the center of the Scd galaxy UGC 8255. The projection of the distance from the SN to the galaxy center onto the plane of the sky is 14.6 kpc and this is only the lower limit for the true distance. The galaxy radius to the 25 $m_B/\square''$ isophote is $46''$, or 10.9 kpc (de Vaucouleurs et al. 1991); consequently, the relative distance of the SN from the galaxy center is 1.34. Wang et al. (2008) plotted the distribution of SNe with various decline rates Δm_{15} in relative radial galactocentric distance. This plot has no objects in a fairly wide neighborhood of the point occupied by SN 2009nr. Thus, no SNe with such a high luminosity at such a large relative galactocentric distance have been observed previously. This is of great importance for elucidating the nature of the 1991T-class SNe Ia. Our estimates of the ^{56}Ni mass for SNe 1991T, 1998es, and 2009nr show that

$M(^{56}\mathrm{Ni}) > 0.8 M_\odot$ (possibly, even more than 1 $M_\odot$) for all three objects. It is believed that during the explosion of white dwarfs with a mass equal to the Chandrasekhar limit, the amount of synthesized ^{56}Ni lies within the range from 0.4 to 0.8 $M_\odot$ (see, e.g., Mazzali et al. 2001). It can be surmised that the outbursts of SNe similar to SN 2009nr are explained by the explosions of objects with a mass larger than the Chandrasekhar limit. As we see from the above arguments, SN 2009nr obviously belonged to the old halo population of the spiral galaxy UGC 8255; the same conclusion was reached by Khan et al. (2011). In this case, the explosion probably occurred after the merger of white dwarfs; this assumption can explain both the large mass and the long lifetime of the system before its outburst.

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